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US Army Corps of Engineers
Topographic Engineering Center

Evaluation of the Bathyscan Sweep Survey System

Anthony Niles

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The U.S. Army Corps of Engineers has an interest in hydrographic survey "sweep" systems, which produce depth soundings over the total bottom area. Such systems can have significant advantages, such as shorter survey times and more complete bottom representations, over the single-trace systems commonly used in the Corps. Such a sweep system, the Bathyscan Hydrographic Survey System that uses interferometric side-scan sonar, was demonstrated to the Corps. The Bathyscan proved to be a well-engineered and innovative design that would be well suited to Corps reconnaissance surveys. Although the system was not survey ready due to some minor software problems and an error in an input parameter, the Bathyscan may be well-suited to condition and contract-payment surveys performed by the Corps.

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PREFACE

The work being reported was done under the U.S. Army Corps of Engineers Civil Works Surveying and Mapping Research Program, Work Unit 32435, "Equipment Evaluation and Software Support."

The work was performed during the period September 1990 to October 1990 under the supervision of S.R. DeLoach, Chief, Precise Survey Branch; P.J. Cervarich, Chief, Surveying Division; and R.J. Orsinger, Director, Topographic Developments Laboratory.

Mr. Walter E. Boge was Director, and LTC John F. Olesak was Commander and Deputy Director of the Topographic Engineering Center at the time of publication of this report.

ACKNOWLEDGMENTS

The demonstration of the Bathyscan system to the U.S. Army Corps of Engineers (USACE) was initiated by William Murden of Murden Marine, Limited. Mr. Murden has a long history of service to USACE, beginning in 1949 with the Norfolk District. In Norfolk, he was involved in surveying, hydro-electric construction, and dredging. In 1958, Mr. Murden transferred to the Office of the Chief of Engineers (OCE) where he worked in programming and planning in construction operations, and eventually, became Chief of the Dredging Division. Upon retiring from USACE in 1988, Mr. Murden began his own consulting business, Murden Marine, Limited.

Mr. Murden has been contracted on an ad-hoc basis with Marconi Underwater Systems Limited of the United Kingdom for consulting work. Marconi, Limited, does frequent business in the United States, primarily through their American subsidiaries, Plessey Naval Systems and Sipican. With Marconi's recent development of the Bathyscan side-scan interferometric system, Mr. Murden realized potential use of the system to USACE. Consequently, he arranged a meeting between OCE, the Topographic Engineering Center (TEC)[1], the Savannah District, and Marconi in February 1990. As a result of this meeting, Marconi agreed to demonstrate their Bathyscan system, (at no cost to the government), to USACE aboard a USACE hydrographic survey vessel. USACE designated TEC as the coordinator, and the Savannah District as the host with the use of their vessel, the Halcyon.

Special recognition goes to Marconi Underwater Systems for demonstrating their system to USACE. Marconi has cooperated with USACE and has obliged many USACE requests, such as modifying their system to match USACE's 200 kHz sounding frequency.

Recognition also goes to the Savannah Hydrographic Survey Section who not only made available the Halcyon with crew for two weeks, but also handled many other planning functions, such as accommodations for USACE attendees.

A complete and unbiased evaluation of the Bathyscan system was made possible with the help of Mr. David Caulfield of Caulfield Engineering. Mr. Caulfield's services were obtained by TEC through a Short Term Analysis Service agreement. Mr. Caulfield, a leading authority in underwater acoustics, has also provided technical services to the Waterways Experiment Station, and his expertise has been invaluable to USACE.

[1]In October 1991, the name of the U.S. Army Engineer Topographic Laboratories (ETL) was changed to the U.S. Army Topographic Engineering Center (TEC). The new name will be used throughout this report.

EXECUTIVE SUMMARY

The Bathyscan Hydrographic Survey System, produced by Marconi Underwater Systems Limited, is a swath-sounding system that uses interferometric side-scan sonar. The system is designed primarily for operation using a towfish. Data is collected, processed, and gridded using an on-board computer. The wide swath of the system enables it to perform surveys in less time than other systems used in USACE.

The Bathyscan system was demonstrated to USACE in Savannah Harbor on 24-28 September 1990, with the Topographic Engineering Center (TEC) coordinating the demonstration and subsequent evaluation. During this time, surveys were performed over a designated test area using the Bathyscan and a Ross sounding system produced by Ross Laboratories, Inc., and used by the Savannah District. The TEC compared the results and evaluated the technology and its application to USACE hydrographic surveying.

The system design and engineering of the Bathyscan appear to be valid and effective. The calibration procedures for towfish stability and the system's interface to the navigation system, critical for a system of this complexity, were complete and well done. During the test surveys, the Bathyscan performed reliably.

Survey data sets were collected over two days during the test period. The post-processed data, completed one to two days after the survey, were then analyzed and compared to the Ross data. The Bathyscan data sets showed poor consistency and differed from the Ross data by more than a foot. Marconi engineers later discovered a simple, but significant, error in the positional offset of the towfish, rendering the post-processed data sets invalid. The Marconi engineers also determined that the swath width needed to be reduced by approximately 15 percent to make errors due to salinity variations negligible. Upon reprocessing the sounding data with the corrected offset and the shortened swath, the data appeared consistent and valid.

The final results suggest that the Bathyscan would be well suited for reconnaissance surveys and may be capable of condition surveys. However, further tests of the system are needed to determine if the Bathyscan is capable of payment survey accuracy. Further experience with the salinity variations and confines of typical American waterways and updated processing capabilities would enable Marconi engineers to produce a fast, ready-to-use system for USACE surveys.

The system could be improved with a more powerful computer that would enable data to be stored in a more manageable format and enable a more powerful programming language to be used. A capability to perform surveys and to process results quickly was not demonstrated, since valid data was not produced until 6 weeks after the demonstration. This delay may not be indicative of the true capability of the system since the simple offset error was not discovered until after the Savannah demonstrations.

BACKGROUND

The demonstration and evaluation of the Bathyscan hydrographic survey system is a project in the Survey and Mapping Research Program. The purpose of this program is to present new technology to USACE districts and to evaluate products that adequately represent this new technology. Also, in this program software is developed that is needed by surveying and mapping offices but is not available commercially. Projects done under this program include evaluating total station instruments and developing the survey programs GEODATCO and CORPSCON.

It should be noted that USACE's sole purpose for this demonstration is the presentation and evaluation of side-scan interferometric sonar for hydrographic surveying within USACE. Other systems that use this technology are commercially available, although their accuracies and applicability to USACE surveying has not been investigated. USACE is not endorsing any single system or manufacturer with this demonstration. Readers of this report should regard any presented evaluations, favorable or unfavorable, as guidelines for evaluating any similar side-scan survey system.

Much of the information in this report is from Mr. Caulfield's final report provided to TEC from Caufield Engineering. A copy of this report can be obtained from the U.S. Army Topographic Engineering Center, CETEC-TL-SP (ATTN: Mr. Anthony Niles), Building 2592, Fort Belvoir, VA 22060-5546, or telephone (703) 355-2766.

Technical Discussion

A complete description of the Bathyscan system is presented in the document Description of the Bathyscan Continuous Swath Depth Sounder by Marconi Underwater Systems.[2] That document is used for an overview of the system and its operation.

Technical Description

The Bathyscan is a swath-sounding system available in 100 or 300 kHz sounding frequencies. A system was modified for 200 kHz for these tests to match the frequency of the Ross system to be used for comparisons. Swaths of 650 to 1600 feet in width are possible depending on the water depth and the frequency used. The system can operate in water depths up to 650 feet.

The Bathyscan is a development from side-scan sonar technology. Although a suitable graphic recorder and conventional signal-processing amplifiers are added, the Bathyscan still retains the capability of producing conventional side-scan plots. Figure 1 shows the system schematic and Figure 2 shows the towfish. The survey capability of the Bathyscan arises from using two transducers for the interferometric detection of the returning sonar pulse. By measuring the phase difference of the returning signal, one can determine the direction of the signal, Θ, from the following formula:

$$\Psi = S*\sin(\Theta) \ / \ (2*\pi*\lambda)$$

where

Ψ = phase difference

S = separation between transducers

Θ = angle between signal and horizontal plane

λ = acoustic wavelength

By knowing the range of the signal and using basic trigonometry, one can determine the depth from the towfish to the bottom (see Figure 3). Adding the towfish depth, determined by a pressure sensor and heavemeter in the towfish, produces the final bottom depth.

Because the angle of the signal changes rapidly in the near vertical, depth data are impossible to determine in this area and thus a data gap exists. This problem is solved by adding a vertical echo sounder, which is also used as a check on the depth profiles.

The stated accuracy for the measurement of Θ is $\pm$/- 0.2 degree. As a result, for a range of 172 feet, the maximum range used in these tests, a depth measurement accuracy of $\pm$/- 0.6 foot is theoretically possible. The accuracy depends on the calibration of all the systems in the towfish and on the proper integration of the navigational data, which is discussed in more detail below. The sonar outputs a 0.2 ms pulse alternately to port and starboard every 0.200 seconds at the 200 kHz system frequency. The beam width of each array is narrow in the horizontal plane, approximately

[2] Description of the Bathyscan Continuous Swath Depth Sounder, The Marconi Company Limited, Waterloo, England, 1989.

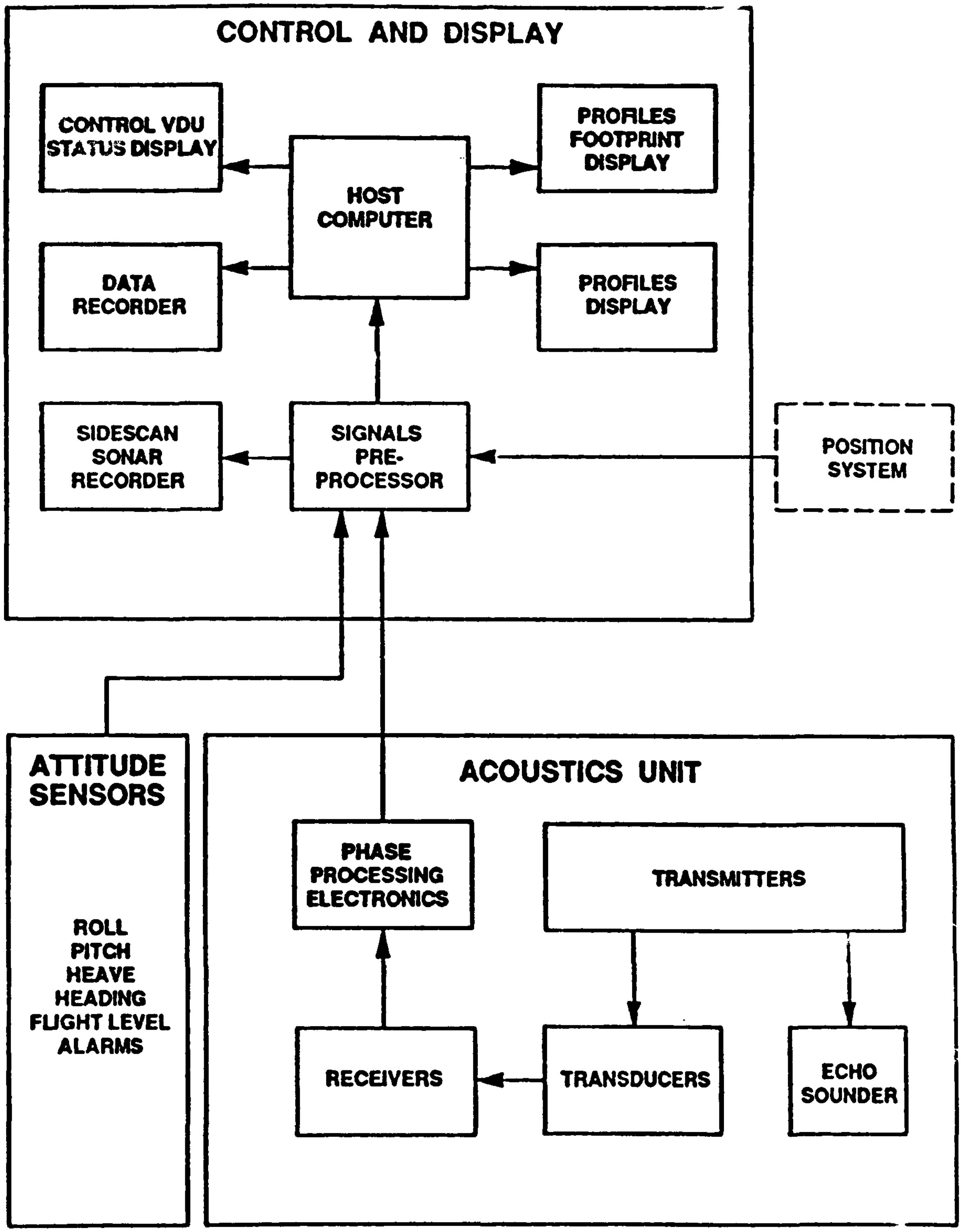


Figure 1. System Schematic.

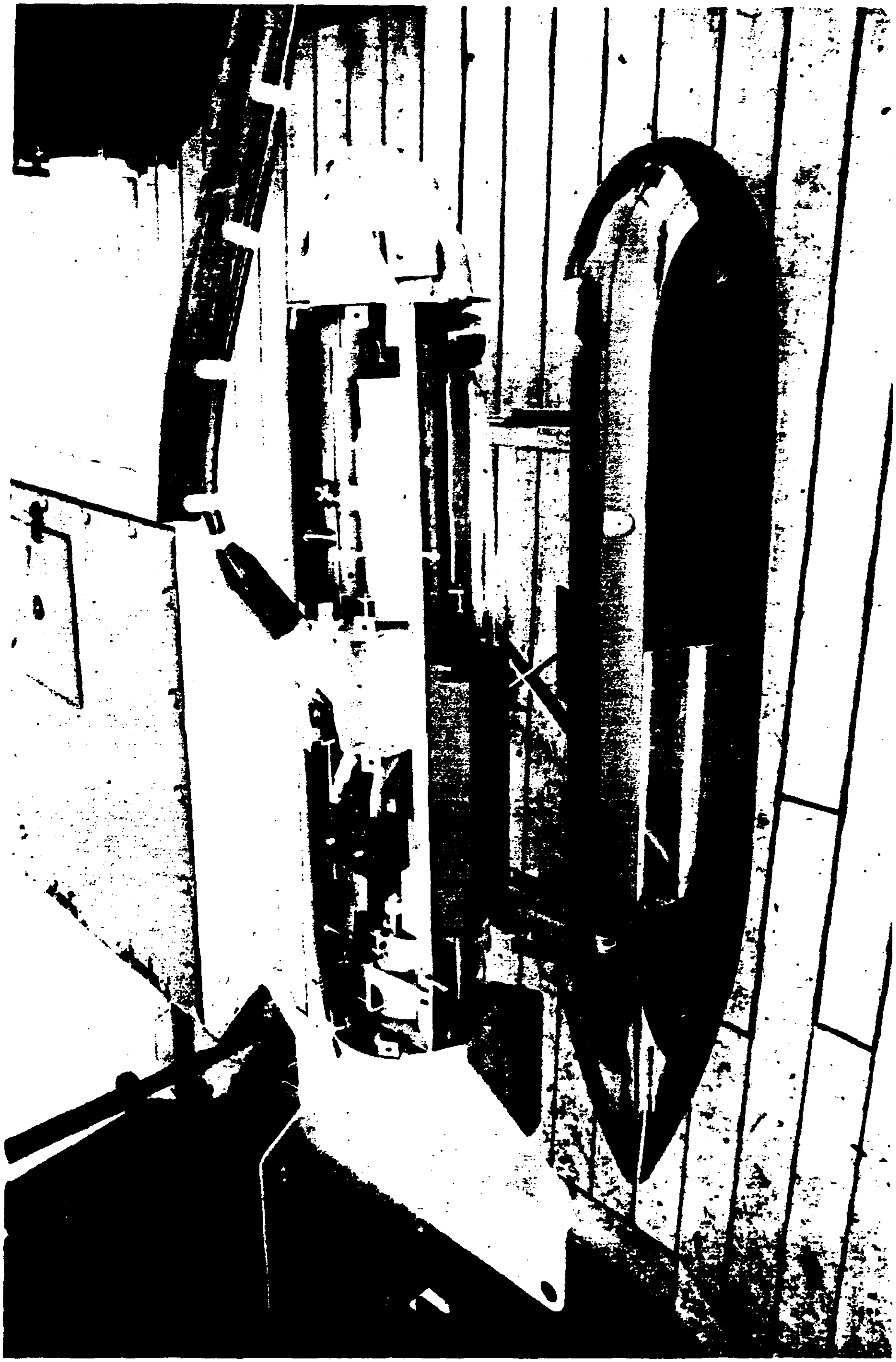
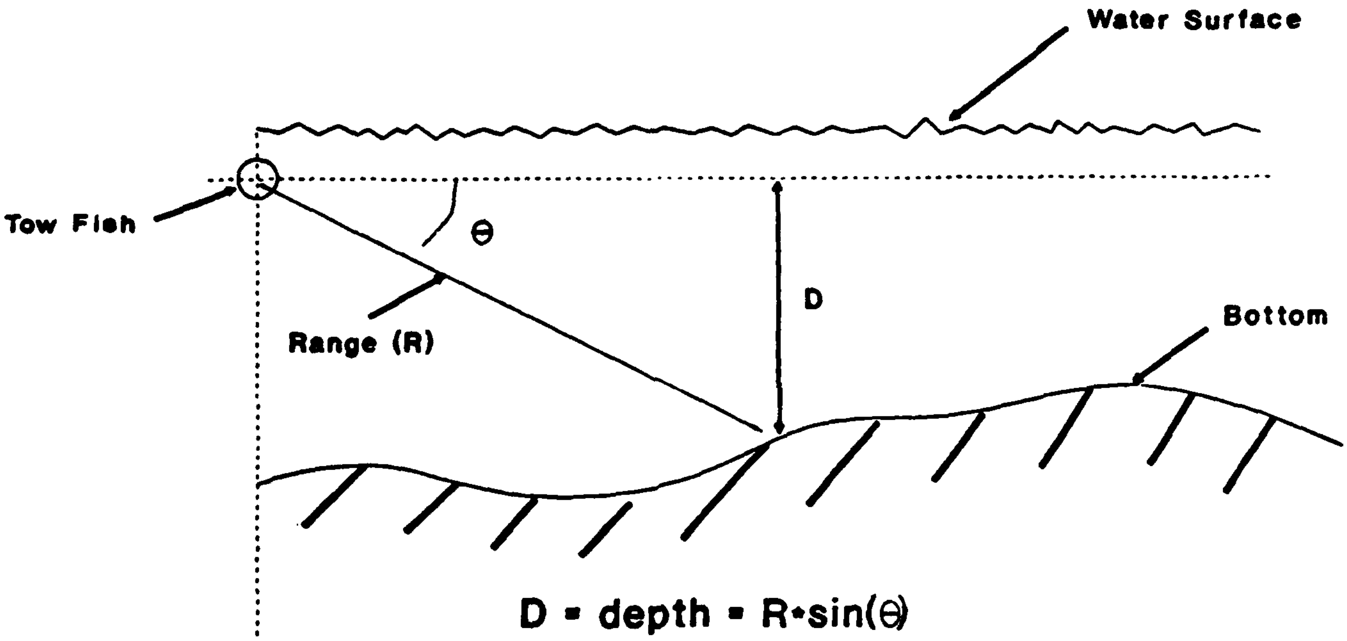


Figure 2. Towfish.

Depth Calculation



D = depth = R∗sin(Θ)

Θ = angle of sonar pulse, as determined on previous page

R = (T/2) ∗ C

T = time from transmit to receive

C = sound velocity

Figure 3. Depth Calculation.

1.5 degrees, but very wide in the vertical to provide long cross-track ranges while retaining angular resolution. Real-time processing takes place in two stages. Sonar signals received on each transducer are digitized and combined to produce phase measurements in a custom built preprocessor. The phase ambiguities are removed, and the signals are converted into depth measurements in the main computer, where corrections from the attitude data are also applied. The data are recorded on a compact large capacity tape recorder and are displayed for the operator.

The system is designed primarily for operation from a towfish, which eliminates interference from turbulence around the ship's hull and enables portability from one ship to another. The advantage of portability was demonstrated when it became necessary to change ships on short notice immediately before the demonstration. The towfish also enables an improved tow depth when unfavorable sonar conditions are encountered. However, it is also possible for the transducers to be hull-mounted. Such a system has not been tested by USACE.

Navigation interface to the Del Norte UHF range navigation system used for these tests was via a RS-232 interface. The final data output for the comparisons was presented on a digital tape, which was then interfaced to an Intergraph workstation. This computer system was set up on site for aiding in the comparison of the systems. During these tests, the survey speed varied from approximately 3 to 6 knots, and the towfish behaved properly at all speeds. The towfish is towed near the surface to minimize shadow zones, usually inherent in sidescan sonars, so that all points on the sea bed may be measured. An overlap of 30 percent was used for redundancy to increase accuracy.

The Bathyscan has a routine that determines if erroneous navigation data is being received. When a position fix is received, which falls outside a prescribed distance from the previous one or which has an error value larger than acceptable, the computer extrapolated a position from immediate past history using distance and heading increments. This will occur for a short period until a fix is received that falls within a prescribed distance from the last position. If not, an alarm is sounded and plotting ceases until accurate positioning is reestablished. During these tests no alarm was sounded with respect to the navigation.

By using post-processing procedures, the surveyor is able to examine all or any of the data at all stages. The depth measurements can be presented graphically in matrix form on any chosen scale, from 1:400 to 1:10,000 or smaller; by either the soundings at the grid intercepts or the representative or lease-depth from each grid unit. The soundings can be color banded, or colored contours can be plotted at a number of chosen intervals. The soundings can also be plotted, in isometric, pseudo 3D form in color-banded form or in monochrome.

Calibration Procedures. Because of the complexity of any side-scan swath bathymetry system, the detailed calibration procedures for towfish stability and the system's tie-in to 3D reference data base with respect to the navigation is critical. This section reviews the excellent built-in calibration procedure used in the Bathyscan system. The ability to examine the stability factors and to build up historical trends in the acquisition computer is crucial to the system's ability to be used as a surveying tool. Each of the major calibration procedures will be reviewed briefly in the following subsections, which will provide needed background information for the following data comparison.

Magnetic Calibration. The towfish direction (bearing) relative to the X-Y coordinates of the navigation system, after correction for offset, must be determined very precisely since the horizontal beam width of the system is less than 2 degrees. An instantaneous bearing is derived from a magnetic flux gate compass. The Bathyscan Group has derived an automated "swing the compass" technique for calibrating the master magnetic flux compass in the towfish.

This technique involves rigging the towfish in the operational position relative to the vessel. This is important as magnetic components on the vessel can influence the local magnetic field. The calibration is accomplished by swinging the vessel in a slow 360 degree turn to port while storing all the magnetic bearings, and then making another complete turn to the starboard again storing all the magnetic bearings. Up to 6000 bearings can be stored. The local magnetic variance is also stored in the computer at this time. This test was demonstrated, and worked well. The data was stored in the computer to aid in the initial system calibration and in the post-processing calibration. This calibration was similar to swinging an airplane's or a ship's compass to obtain the local variations.

This calibration must be conducted whenever the system is installed on a new ship and only needs repeating if the magnetic properties of the ship change. Each swing takes 12 minutes and requires 250 yards of open water to perform.

Positional Processing Delay. A separate correction is applied for the delay in processing the navigational sensor data and for the associate positional information with the appropriate sounding data from the Bathyscan. The size of the correction is determined by identifying common features from comparison of two adjacent overlapping sets of data taken from runs carried out in opposing directions. This calibration is not required if time-tagged positional data is available (not available for these tests).

Transducer Plate Angle Calibration. This calibration is required to determine the relative angle of each transducer plate to the roll gyro vertical. Three short survey lines are run with the adjacent lines being in opposite directions. From the data gathered the two port and two starboard sets of soundings are compared. Any offset between the soundings in each pair is identified by a software procedure. A plate angle correction for each transducer is thereafter applied automatically.

Since this calibration depends on the comparison of two sonar images of the same part of the seabed, it requires that the positional processing delay have already been determined. If this has not been done, then the transducer plate angle calibration must be performed over a relatively smooth seabed.

The transducer plate angle calibration normally takes approximately two hours to perform and is only required after assembly or reassembly of the towfish. The survey calibration lines must be gathered at a steady speed and heading and must be about 1000 feet long. They must also be offset to enable 50 percent overlap between lines.

Pressure - Depth - Position Calibration. The towfish depth varies as a function of speed and the amount of tow cable deployed. The towfish also has an aft offset that varies as a function of speed. The Bathyscan system can be calibrated in real time for all of these variances.

First, the amount of tow cable deployed is measured precisely. Since the amount deployed from the tow point is known precisely with respect to the navigation antenna, the exact position of the towfish can be calculated by noting the changes in pressure in the towfish. As the towfish moves aft, it must rise slightly and the pressure change is used to compute the aft offset.

Second, the depth stability of the towfish can be monitored by recording the output of the pressure transducer. An accelerometer is also available to compensate for both short-term wave motion and long-term heave. Towfish roll and pitch is calculated from the output of the gyro.

The outputs from the magnetic compass, gyroscope, vertical accelerometer, and the pressure sensor are combined with the acoustic profiles in calculating the depths. All of the data are used to create real-time displays that enable the system performance to be monitored continuously during the survey. If the towfish stability is outside the range for good data, visual alarms are provided on the computer screen. This system was fully operational during the field tests.

Amplifier Calibration and S/N Optimization. As stated earlier, the system uses phase detection to determine the angle at a given travel time to determine the depth at that angle. In order for this detection concept to work properly, the signal must be processed by an Automatic Gain Control (AGC) function. Basically, this function limits the received signal so that the phase-detection process is optimum. The system can generate a test signal to pass through the various amplifiers and detectors. This test signal tests the AGC function as well as the phase-detection system. The output of the test signal is monitored in color on the computer monitor. This test procedure operated properly during the field tests.

The phase detection used to detect the phase angles is done on different pairs of receivers separated by different multiples of the wavelength, which insures that unique solutions of the angle are obtained. Failure to detect the angle though this multiple detection scheme is an indication of poor signal-to-noise ratio. This latter detection is then rejected. A complete review of the detection process shows that the sonar concepts are correct.

Sound Velocity Correction. The system has the ability to input the local sound velocity corrections. During this test, the local sound velocity was computed by the Ross system using soundings off the ball check device on board the Halcyon. This velocity parameter was used to initialize the Bathyscan system.

Calibration Summary. All of the necessary sensing engineering with respect to the towfish appears to have been completed to ensure that the sonar data is correct. The system software takes this data and computes all the necessary corrections so that the depth and location of each depth pixel is known. Although the details of all the final processing algorithms were not made available for review, the color imaging of the survey data showed that the data were consistent in any one area, and the calibration factors all appeared to function properly.

FIELD TEST PROCEDURES

In order to evaluate the Bathyscan as a survey tool, TEC compared the system to the Ross echo-sounding system used in the Savannah District. The Ross system was selected because it is typical of those commonly used by USACE districts and dredging contractors, and it is accepted as a valid survey tool. Since the forms of the data between the two systems are quite different (dense grid data versus single trace), only the accuracies are compared.

Because of its large swath width, the Bathyscan system has the potential of performing surveys in less time than any other system used in USACE. The density of the data could also produce a more precise representation of the seabed.

Also, the Bathyscan was tested to determine the system's ability to detect underwater objects. Three pyramids were placed on the river bottom for this test, and details are given below.

Survey Data Collection. The designated test area is in the Savannah Harbor near the mouth of the river. The area is approximately 1000 by 1000 feet and is aligned with the channel centerline. Figure 4 shows a section of a chart produced the previous year that has the test area outline. This area was deemed favorable because it has sufficient side-slope, has a firm bottom with little suspended sediment, and is near a suitable calibration point (an offshore mooring platform).

The vessel used for these tests was the survey boat Halcyon, a 65-foot SWATH (Small Waterplane Area Twin Hull) design with torpedo-like tubes at the bottom of each hull. Although, the Halcyon has an active ballast system that produces a very stable platform for surveying, even in rough seas, the stabilizing system was not used during these tests in order to ensure that the vessel had a consistent draft for all tests. The Halcyon has an on-board crane that was well-suited for deploying the towfish, and the vessel was able to accommodate all guests during the two days of demonstrations.

The test plan was to perform two surveys of the area using the Ross system and two surveys using the Bathyscan. The data sets from each system were to be compared (to each other) to determine the consistency of each system. A data set from the Ross and the Bathyscan systems would then be compared. If possible, a survey would be performed using both systems simultaneously, thus reducing or eliminating some errors, such as navigation system inaccuracies and tidal errors. However, the Ross and Bathyscan systems each required different forms of data from the navigation system; the former required raw ranges and the latter required X-Y coordinates. Thus, the simultaneous survey was not possible for these tests.

The four test surveys were to be performed on 24 September 1990, the data was to be processed on 25 September, and the results would be presented the following day. However, problems were encountered with the intended schedule. The Halcyon developed mechanical trouble the previous week when it was returning from a survey, and the problem was not corrected until 22 September. Therefore, the trial and calibration runs that were planned for 20 and 21 September were delayed until 24 September. Then as much survey data as time permitted was collected.

A calibration and test run of the Del Norte UHF positioning system was first performed. The system was initialized with known coordinates at a lash facility in the area. The Halcyon then made a run to the extreme end of the survey area (approximately 1500 feet) and returned to the calibration point. The positioning system agreed to the known coordinates within 2.5 feet. Additional checks of the positioning system were made after each survey, and in each case the system was accurate within 3 feet; well within the manufacturer's specifications.

Bathyscan Survey. Bathyscan calibration procedures were then performed. A magnetometer calibration run was first made by running the Halcyon in a wide, slow circle. Four longitudinal gyro calibration runs were then made, as previously described in the Calibration Procedures. These runs are required whenever the system is installed on a new vessel.

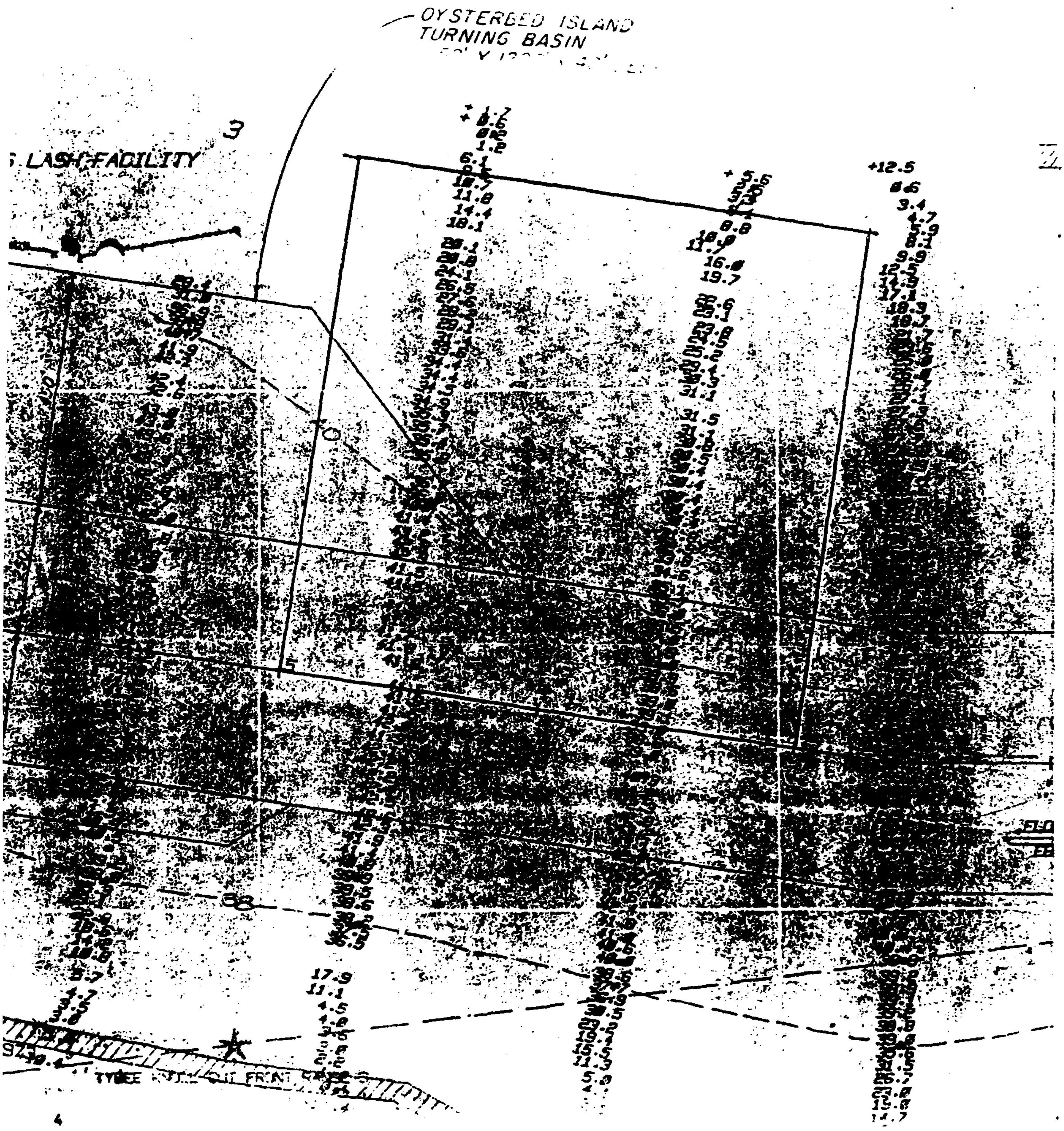


Figure 4. Survey Test Area.

A survey was then made of the designated test area. Since the lines had to be run at 3 to 4 knots, it was determined that all survey lines must be run against the tidal flow. This slow speed was required to produce the meter-gridded data for the evaluations. Normally, 5-meter grids are produced and the vessel is run at 5 to 8 knots. Six longitudinal survey lines, approximately 150 feet apart, were produced. Figure 5 shows a 3-D contour plot produced on board the Halcyon. The toe-line of the channel is added to the plot for clarity.

The towfish and transducers functioned well, unless the unit was bumped during the survey. When turning into the first survey line, the centrifugal force caused the towfish to contact the vessel's hull, upsetting the accelerometers. Once the transducers were resettled, the survey line was restarted. Subsequently, all vessel turns were made to port to avoid contacting the towfish.

During this time and during all the test surveys, tide readings were observed and recorded at frequent intervals. A tide staff at the mooring platform was used, no more than 1000 feet from the test area, and readings were recorded whenever the tide changed by one-tenth of a foot. This information was used during post-processing to reference all surveys to a common water level.

Ross Survey. A survey of the area was then performed using the Ross single-trace system. Nine longitudinal lines, 100 feet apart, were made at a speed of 5 knots. After the positioning system was checked and recalibrated, a second check survey was made consisting of four cross-sectional lines, 200 feet apart. Figure 6 shows the overlapping survey data sets, both plotted on board the Halcyon.

Additional Bathyscan Survey. As mentioned previously, a second Bathyscan survey was to be performed; however, there was insufficient time to collect this data on the 24th. Therefore, the evaluation and presentation given on the 26th to USACE representatives was based on this single survey performed with the Bathyscan. A second survey was performed on the 28th and the results are included in this report.

Underwater Object Detection. Three plywood pyramid targets were used to test the Bathyscan's ability to detect underwater objects. The targets which had been constructed for echo-sounding tests at the Detroit District and were shipped to Savannah for testing with the Bathyscan system, were 2 to 3 feet wide and were 2 to 4 feet high.

The test consisted of placing the three targets in a group to the North side of the channel, out of the way of normal traffic. Each target was buoyed so that it could be identified when the Bathyscan towfish passed by. The Bathyscan system was limited, at this time only, to 5 pings per second. This meant that at normal vessel speeds of 3 knots that only one or two pings would be available to reflect off of the targets. The system was further limited, again at this time only, by the use of the AGC limiting circuit that prevented full-scale presentation of the reflected signals in a normal side-scan display.

Even with these limitations, the graphic record showed dark spots at the appropriate times and ranges that would correspond to the targets. The attached scope showed that the corresponding signals in this area exhibited good signal-to-noise ratio, even with the clipping required due to the AGC circuits.

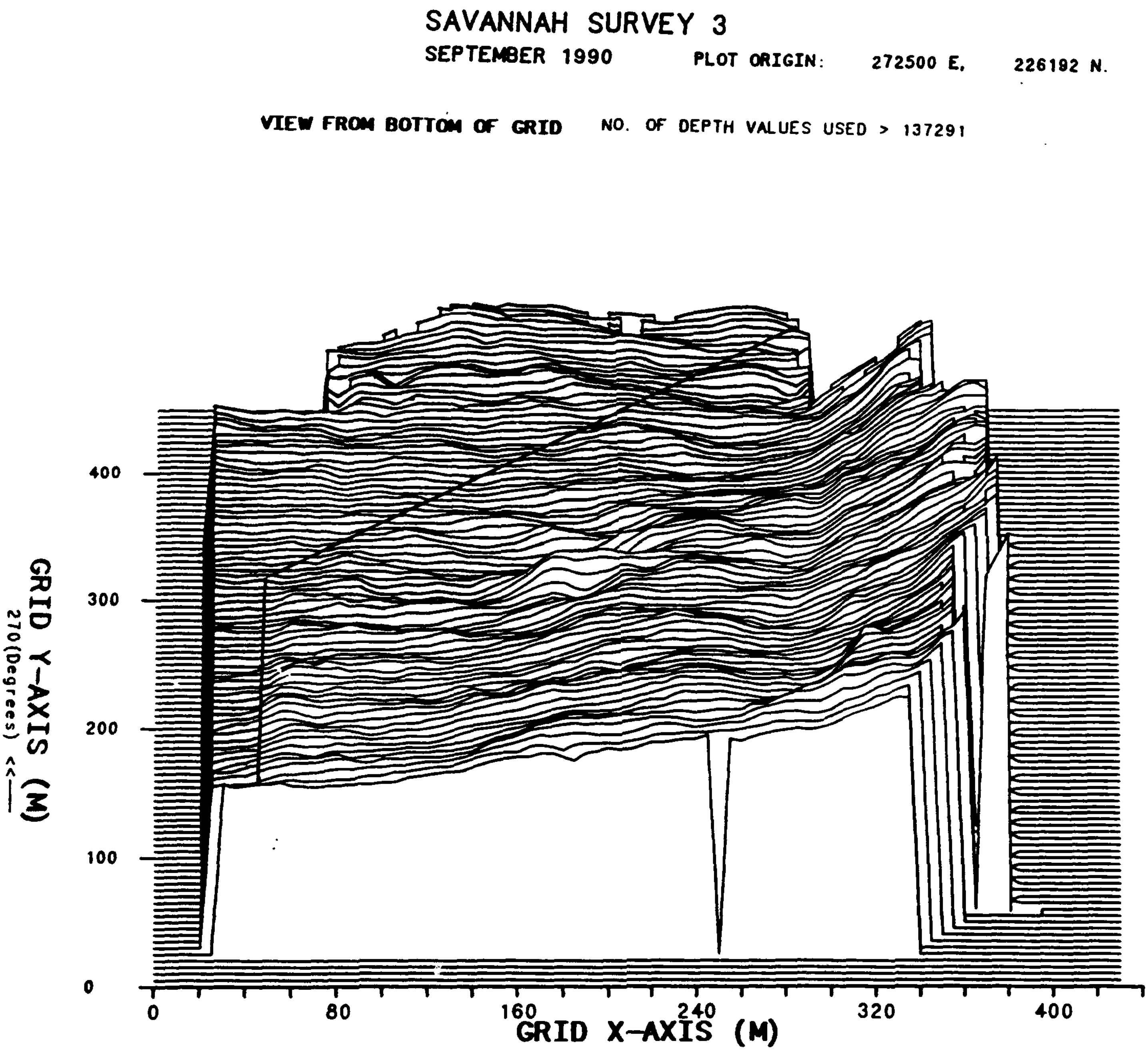


Figure 5. Bathyscan 3-D Plot.

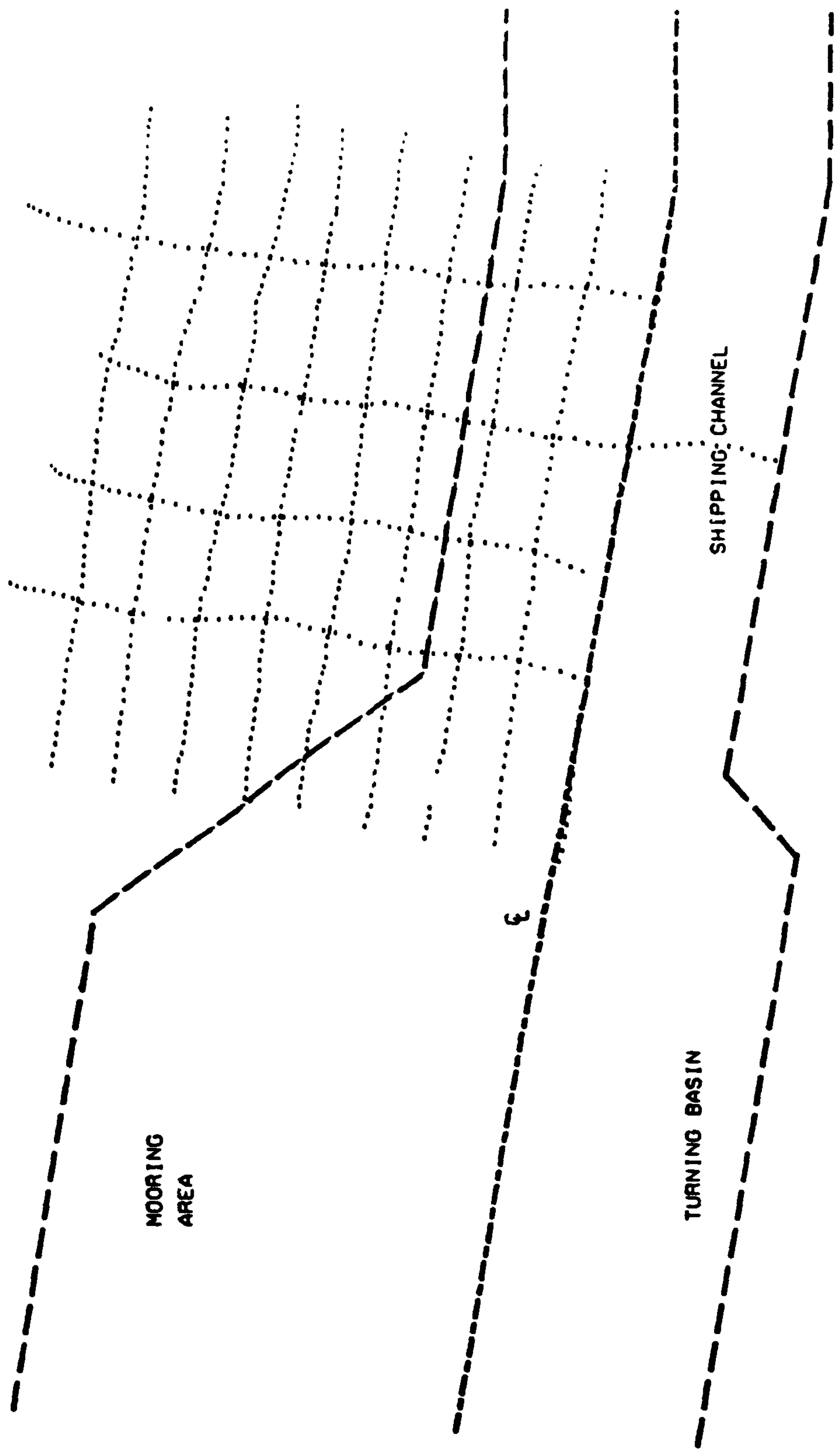


Figure 6. Plot of Ross Survey Data.

Although very limited in testing, a modified Bathyscan system appears to be an important tool for finding such an upright target. The major modification being a faster ping rate and limiting the system range so that the processing would be an obstruction detector rather than a bottom mapper. This modification would mainly involve changes in software and would not require any major modification to the Bathyscan hardware, except for switching in the appropriate display amplifiers.

As emphasized by Mr. Caulfield, Caufield Associates, a system configured for bottom mapping would not be well-suited for object detection, and vice-versa. However, with minor modifications, the Bathyscan could easily switch between the two modes and could be capable of performing each function successfully.

DATA COMPARISON

Data analyses and comparisons were performed on an Intergraph workstation. The statistical routines were developed by TEC, and the routines used for graphic comparisons were commonly available software packages from Intergraph.

Survey Accuracy Standards. The following data comparisons and overall system accuracy are referenced to USACE accuracy standards.[3] The three general classes of hydrographic surveys in USACE are defined as follows:

Survey Class	Purpose	Horizontal Positioning Accuracy (RMS)	Depth Accuracy
1	Contract Payment	3 meters	± 0.5 foot
2	Project Condition	6 meters	± 1.0 foot
3	Reconnaissance	10 to 100 meters	± 1.5 feet

The Bathyscan is thus evaluated as a tool for surveys performed for and by USACE. Also, as described in the field test procedures, the system's ability for object detection was evaluated.

Ross Data Sets. Following the collection of survey data on the 24th, the Ross data sets (a set consisting of profile data and a set of cross-section data) were loaded into the workstation for analysis.

Where the survey lines crossed, the soundings were interpolated to a common X-Y coordinate, and then compared. The results, based on a total of 33 crossing points, are as follows:

Standard Deviation	+ 0.46 foot
Average Deviation	0.35 foot
Maximum Difference	1.37 feet
Bias	- 0.03 foot

[3] Hydrographic Surveying, Engineer Manual, EM 1110-2-1003, Department of the Army.

where the standard deviation, σ, is given by:

$$\sigma = [\sum_{i=1}^{n} (zz_i - \underline{z})^2 \ / \ (n-1)\ ]^{1/2}$$

$$\text{Bias} = \underline{z} = \sum_{i=1}^{n} z_i \ / \ n \qquad \begin{aligned} z_i &= (z_p - z_x)_i \\ z_p &= \text{profile depth} \\ z_x &= \text{cross-section depth} \end{aligned}$$

$$n = \text{number of points compared}$$

and the average deviation is:

$$\text{Average Deviation} = \sum_{i=1}^{n} \mid (z_i - \underline{z}) \mid / \ n$$

These Ross data sets represented typical results that are normally obtained in USACE surveys. The data were also plotted using the Microstation graphics routine, revealing that the maximum deviations occurred on the side-slope, as expected, due to navigation inaccuracies. Nevertheless, the data showed consistency sufficient for all classes of USACE surveys.

Initial Bathyscan Results. The Bathyscan data collected on the 24th was post-processed by Marconi personnel on their PDP-11 computer on the 25th. This post-processing generated the 1-meter gridded data that was then loaded into the Intergraph workstation for subsequent comparisons.

The format of the Bathyscan data initially presented some problems for the analyses. The data consisted of "merged" multiple lines, where all the depths are given in an array that is specified by the boundary coordinates of the survey. There were some minor difficulties because the Bathyscan data had to be converted from meters to feet. Also, the Bathyscan data had been stored as an array of numbers referenced to base navigation references. Because the data array does not store the positions with each depth point, some confusion occurred as the exact format of the header varied from that presented by the Marconi engineers; thus, the exact orientation of the depth array with respect to the coordinates was in question.

The first analysis resulted in very poor correlation with the Ross data and revealed many errors. The data that was presented to demonstration attendees on September 26 had many spikes and false coordinates that, if valid, would indicate depths that were on land. The mean difference between the Bathyscan and Ross depths was over 6 feet.

Further analysis showed that data from a previous channel test run had become merged during postprocessing with the survey data. This was the cause of the coordinates that appeared to be "on land." Also, due to the heading format discrepancy mentioned above, the X-Y coordinates were off by almost 100 meters. The lack of positional information with each data point makes the data cumbersome to handle. This problem can easily be solved, and Marconi/Bathymetrics plans to do this by using a newer computer in their analysis process.

After correction for the positional disparities mentioned above, the data was compared to each Ross data point. Because of the abundance of data points with the Bathyscan system, it was relatively easy for the workstation to select points that occurred almost exactly where the Ross data was taken. The data comparison between 521 points provided the following information:

Standard Deviation	+ 1.55 feet
Average Deviation	1.17 feet
Maximum Difference	+ 8.20 feet
Bias	+ 2.31 feet

where the standard deviation, as given previously, with the following terms:

$$z_i = (z_R - z_B)_i \qquad \bar{z} = \text{Bias} = \sum_{i=1}^{n} z_i \,/\, n$$

z_R = Ross depth
z_B = Bathyscan depth
n = number of points compared

Figure 7 shows comparative plots between the Bathyscan and Ross data at each Ross profile and cross-section line. The vertical scale is exaggerated to illustrate the differences. As shown, the differences in many areas are greater than 1.5 feet, which is larger than that called for in all three survey classes used in USACE.

The second data set, obtained from the Friday survey, was more carefully post-processed by Marconi personnel so that all spikes were removed and there were no erroneous horizontal coordinates. Survey lines were upstream and downstream, rather than in one direction, which Marconi/Bathymetrics engineers concluded enabled better gyro calibration. A data comparison between 608 points reveals the following:

Standard Deviation	+ 1.39 feet
Average Deviation	1.09 feet
Maximum Difference	+ 6.03 feet
Bias	+ 1.48 feet

Figure 8 shows comparative plots between the Bathyscan and Ross data. Again, differences in many cases are larger than 1.5 feet.

Error Analysis. In an effort to understand the deviation and to determine if the variance was spatially related, a simple spatial correlation program developed by Mr. Caulfield was utilized. This program computes the cross-correlation function, Φ, between two sets of arrays, X_d (Ross Data) and Y_d (Bathyscan Data), where the subscript "d" is the distance index along the track with the track being divided into approximate equal increments. The equation for this correlation function is the following:

$$\Phi = \left[\sum_{d=1}^{N} X_d * Y_{d+i}\right] / \text{Norm}$$

where

$$\text{Norm} = \sum_{d=1}^{N} (X_d)^2$$

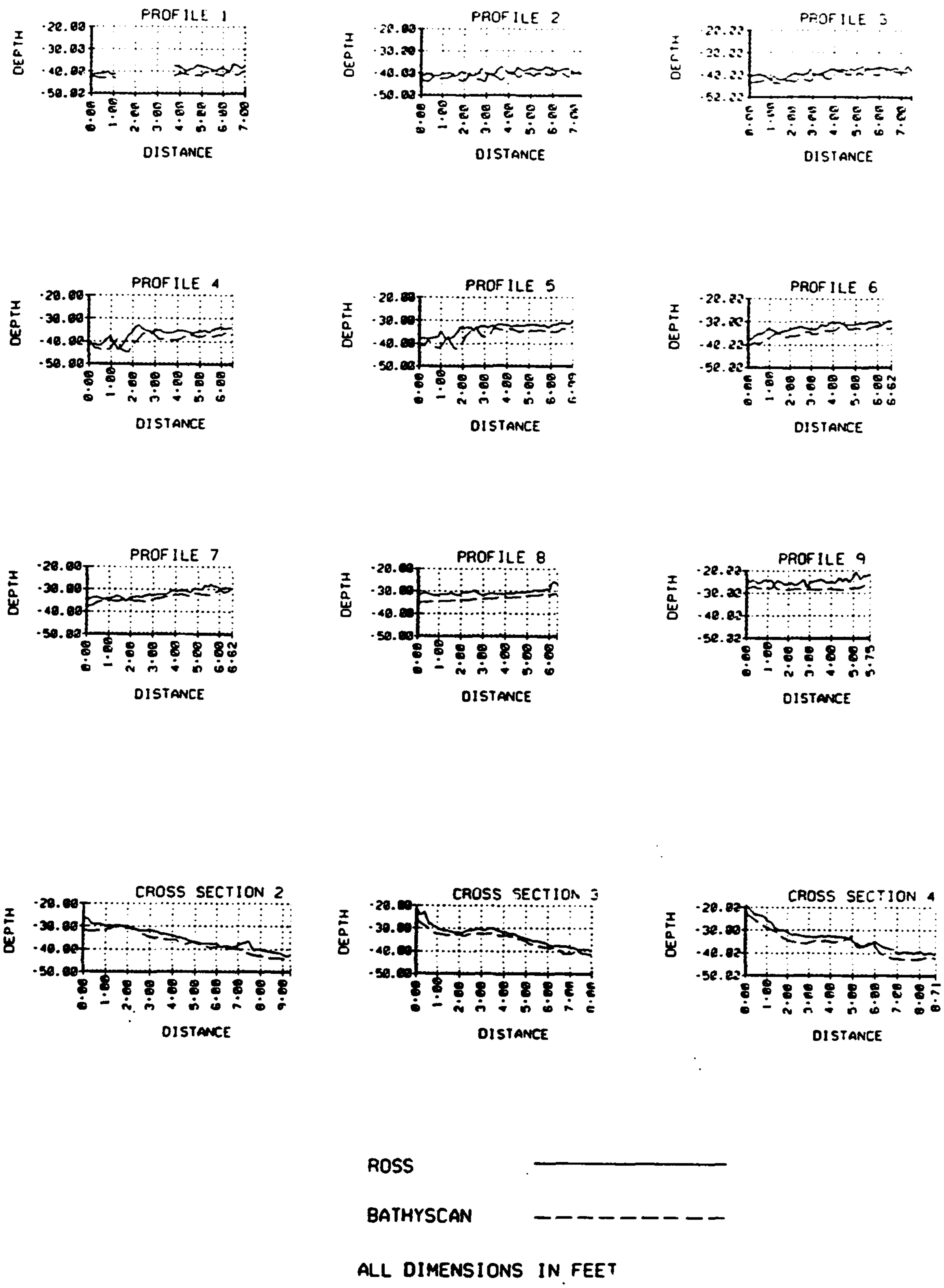


Figure 7. Initial Results for 24 September Survey.

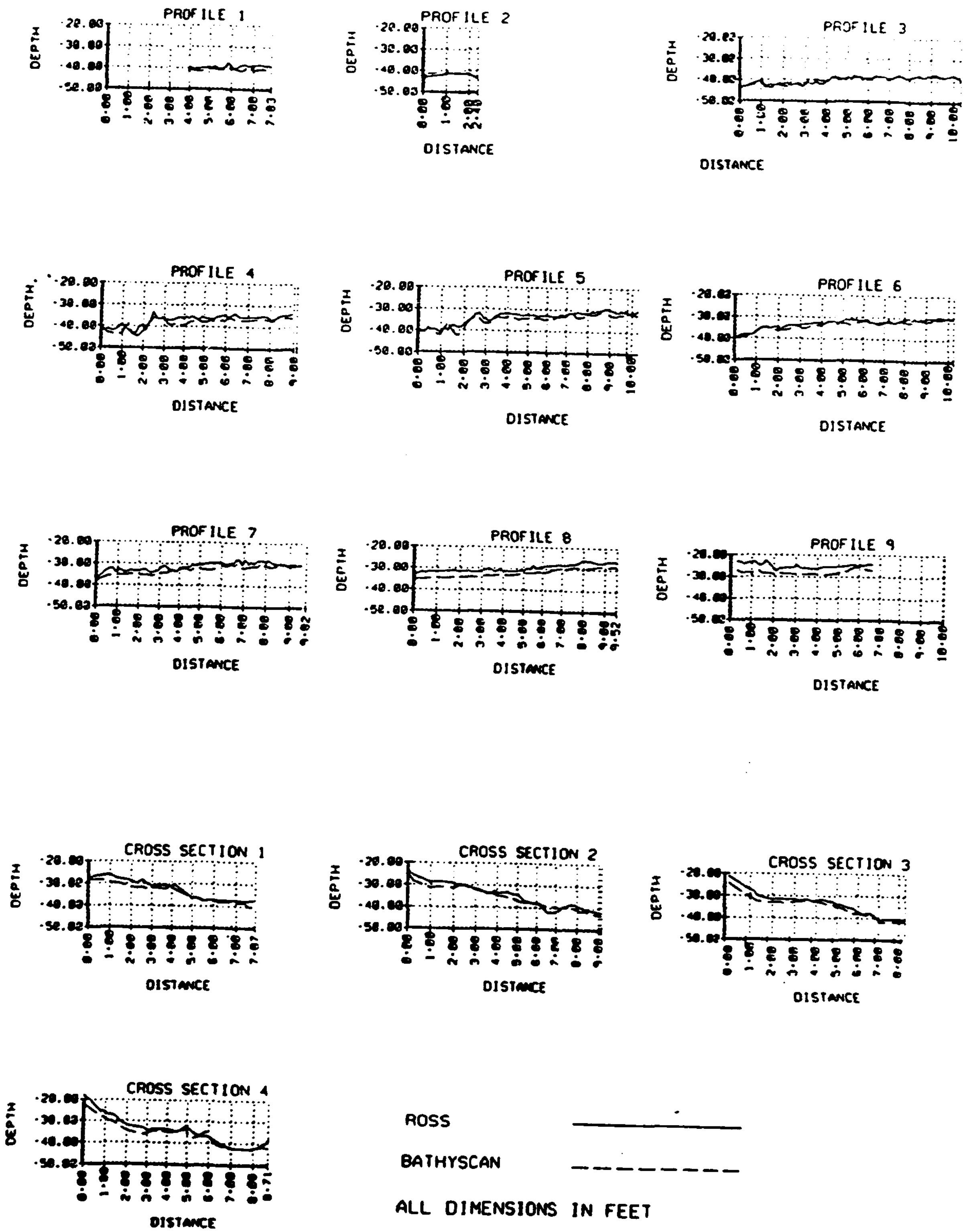


Figure 8. Initial Results for 28 September Survey.

If the Bathyscan data equals the Ross data exactly, the correlation should be 1 with "i" equal to zero. If the data is equal, but off set due to a navigation error, the correlation function should be 1, but off set at some "i"th value. Table 1 gives the results of this correlation measurement for the 9 Ross profiles and 4 Ross cross sections. The profile lines are the East-West lines starting with Profile 1, which is in the channel and working towards the shore, with profile 9 being closest to the shore. The cross section lines run North-South with cross-section 1 being the eastern-most line.

As seen from the table, the peak correlation in most cases occurred at an offset of 1 data point. The average spacing between points was approximately 15 feet, which means that the data sets were off set by as much as this amount in the X and/or Y direction. Since the positioning system showed good accuracy and repeatability, this analysis established in part that there is a problem in the navigation integration with the sonar data.

Post-Survey Analyses. Marconi/Bathymetrics engineers continued to analyze the data and the procedures from the test surveys, and they discovered a simple but significant horizontal positioning error. The applied offset from the positioning system antenna to the towfish was 90° off, which would indicate that the towfish was deployed off the stern rather than starboard. This resulted in a positioning error of 15 feet or more. Marconi engineers reprocessed the data with the new offset and submitted the results to TEC. The results for the reprocessed 24 September data set are as follows:

Standard Deviation	+ 0.69 feet
Average Difference	0.52 feet
Maximum Difference	+ 4.26 feet
Bias	+ 1.43 feet

The results for the reprocessed 28 September data set are

Standard Deviation	$\pm$ 0.82 foot
Average Difference	0.64 foot
Maximum Difference	+ 4.00 feet
Bias	+ 1.16 feet

Figures 9 and 10 show comparative plots of the Ross and revised Bathyscan data. Marconi personnel also concluded that sound velocity variations in the Savannah Harbor, due to temperature and salinity gradients, become significant when the sounding pulse slant range is too large. The range limit for the reprocessed data was thus reduced from 172 feet to 148 feet, which makes the distortion due to temperature and salinity variations negligible. Thus, for a depth of 40 feet, as encountered in the survey area, the Bathyscan system produced swath widths of 3.5 to 4 times the depth. The shortening of the slant range produced some gaps in the data, which resulted in somewhat fewer points for comparison.

As shown in the bias, the data had a consistent difference of approximately 1.1 to 1.5 feet with the Ross data. However, the Bathyscan surveys were consistent with each other to less than 0.5 foot. Thus, the Bathyscan system showed a shallower bottom than the Ross system.

An analysis of the data was made by removing the side-scan data from both data sets, leaving only the echo sounder data. The plotted data again showed good consistency in the two data

Table 1. Survey Line Correlation Results

Line	No. of Samples	Peak	@Pt.	Mid-Pt. Value*
24 September Data set				
Profile 1	39	0.83	40	0.65
Profile 2	41	0.78	42	0.38
Profile 3	46	0.79	47	0.72
Profile 4	39	0.93	40	0.85
Profile 5	49	0.84	50	0.81
Profile 6	46	0.88	45	0.85
Profile 7	46	0.83	45	0.80
Profile 8	38	0.69	37	0.55
Profile 9	35	0.52	38	0.49
X Section 1		- - No Overlap with Bathyscan Data - -		
X Section 2	49	0.95	48	0.90
X Section 3	46	0.96	45	0.88
X Section 4	46	0.96	45	0.86
28 September Data set				
Profile 1	42	0.62	42	←
Profile 2		- - No Overlap with Bathyscan Data - -		
Profile 3	66	0.88	65	0.83
Profile 4	50	0.86	50	←
Profile 5	72	0.92	71	0.86
Profile 6	59	0.92	58	0.85
Profile 7	66	0.85	65	0.81
Profile 8	57	0.95	56	0.89
Profile 9	38	0.36	57	0.22
X Section 1	24	0.97	23	0.87
X Section 2	41	0.95	40	0.86
X Section 3	41	0.98	40	0.87
X Section 4	45	0.98	44	0.90

* ← signifies that the mid-point value is the same as the peak value.

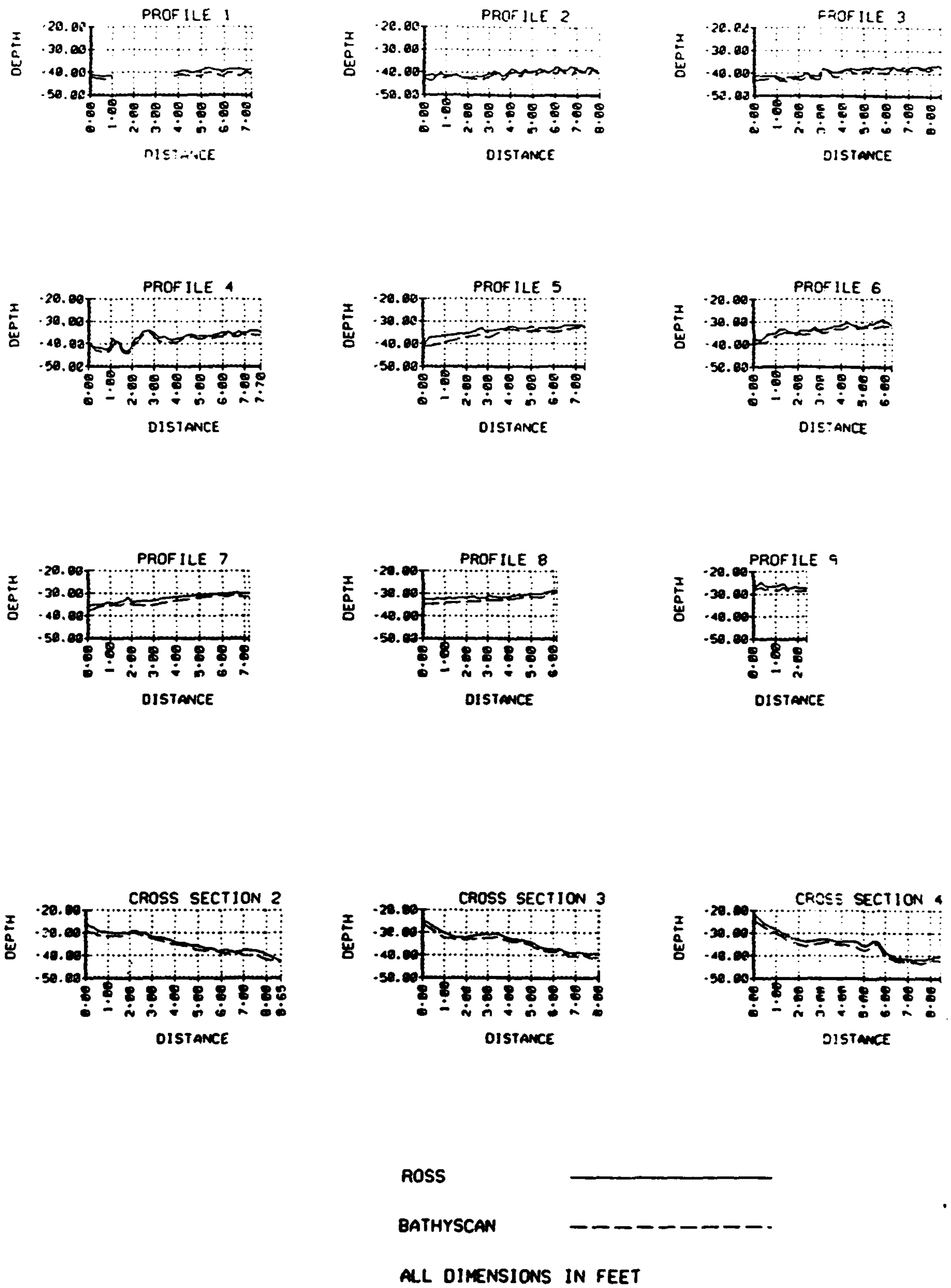


Figure 9. Revised Results for 24 September Survey.

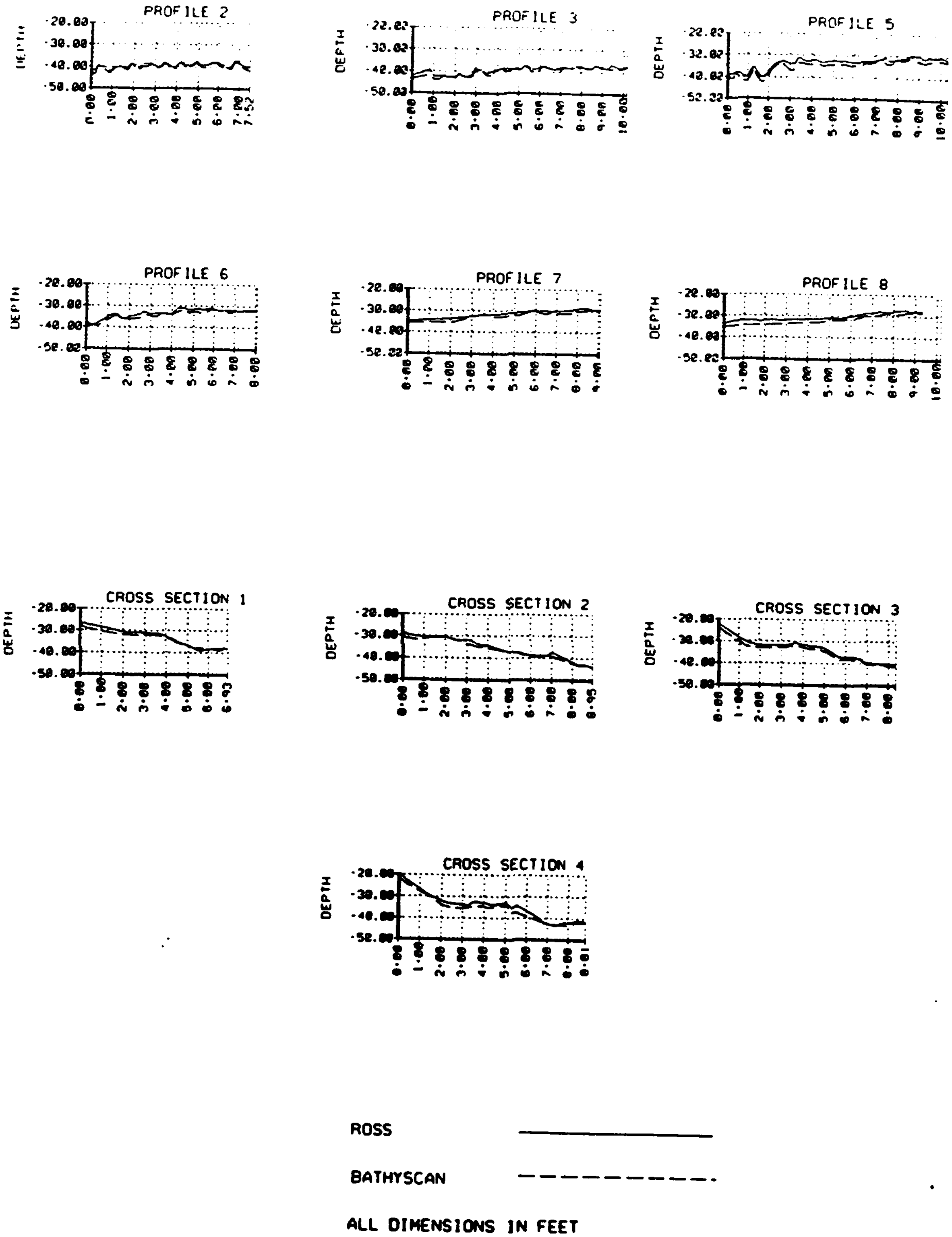


Figure 10. Revised Results for 28 September Survey.

sets and was consistently shallower than the Ross data. A further review of the Marconi documentation revealed that although the side-scan transducers matched the 200 KHz frequency of the Ross system, the echo sounder in the towfish uses 500 KHz frequency. For a hard bottom, this should produce only small differences. The bottom in the test area was assumed to be firm sand, but considerable suspended sediment is known to exist in other areas of the harbor. Although collected bottom samples would have been useful for the analysis, none were taken. Nevertheless, the presence of suspended sediment or soft mud is a reasonable assumption, and could explain the discrepancy in the echo sounder data. The integration of the side-scan with the echo sounder data would result in a consistent discrepancy between the Bathyscan and Ross systems.

Note that this analysis concentrated on the consistency of the data sets, and not on absolute accuracy. This was because of the frequency variation mentioned above, and because of the absence of independent verification of the absolute accuracy of the Ross system. The final processed data showed a system that would be well suited for reconnaissance surveys. If the depths are inaccurate, then the errors are systematic and can be easily compensated for in the software. Although the system also may be capable of condition and payment surveys, further tests would be needed for verification.

CONCLUSIONS

The tests established that the Bathyscan offers some useful capabilities that are not in systems currently used in USACE. The density of the data produces complete coverage of the bottom, which enables more precise seabed mapping. Because of the swath width of the Bathyscan, surveys can be performed in less time than other systems presently used in USACE. A review of the system design shows that the sonar concepts are valid. During the tests the system performed well, with little or no technical problems. The tests have demonstrated that the Bathyscan is capable of reconnaissance surveys and may be capable of condition and payment surveys, although the latter capability can be verified only through further field tests.

The initial processed data sets showed unfavorable consistency and differed from results obtained by the Ross echo-sounding system by more than 2 feet. Marconi engineers discovered a simple, but significant, error in the gridding software that resulted in a horizontal positioning error of more than 15 feet. This rendered the processed data invalid. The soundings were reprocessed with the corrected position offset of the towfish, and the results were much more favorable. Marconi engineers also determined that salinity variations in the savannah Harbor could cause significant errors for wide slant ranges. The slant range was thus limited to 148 feet, or approximately 3.5 times the depth, in the revised data.

The PDP-11 computer used in the Bathyscan system is an old computer with limited capability, by current standards. While the processor appeared adequate during the demonstrations, a newer and more powerful system would significantly reduce postprocessing time and enable data to be stored in a more manageable format. Also, a newer processor would enable a more powerful computer language to be used, such as C or updated FORTRAN, and would make system modifications or troubleshooting easier. Marconi/Bathymetrics engineers intend to adopt such a system.

From the technical data made available on phase detection methods, it appears that the sonar design does make the best depth estimates as a function of the signal-to-noise ratio. Further, for noisy data, the system does not attempt to make any predictions, thus assuring that only "good" data is used.

Using 200 KHz is consistent with the most common sounding frequency used in USACE, and thus allows integration with present adopted USACE survey standards. The future availability of the other frequencies will permit increased flexibility. For example, higher frequencies will allow for better target detection, and lower frequencies will help survey accuracies when suspended sediments occur.

The Bathyscan system, when operating at a higher ping rate and using the proper record amplifiers, appears to have the capability to play an important part in target detection. Although the modifications were not made for these tests, they can be easily made for future tests.

The initial tests indicated that the towfish-mounted system, deployed from a stable survey boat such as the Halcyon, could provide both the portability between regions as well as suitable performance for reconnaissance, condition, and perhaps payment surveys. If the system is to remain on a single vessel, then a more logical configuration of the Bathyscan would be as a hull mounted rather than a towfish configuration. However, such a system has not been examined by USACE.

The Bathyscan system was also evaluated as a ready-to-use system that produces results quickly. This fast capability was not demonstrated in Savannah since the valid results were not produced until 6 weeks after the demonstration. However, this delay may not be indicative of the true capability of the Bathyscan system since the simple offset error was not discovered until after the Savannah demonstrations. By solving this problem and by becoming familiar with typical American waterways, Marconi engineers could produce a system that is capable of providing valid survey results within one day. The one-day results have been demonstrated in the North Sea and in some European waterways.

The system tests and post-analyses have thus revealed that the Bathyscan is a well-designed and innovative system that uses side-scan sonar to produce survey accuracies. Because a simple software gridding error in the Bathyscan invalidated survey results, a survey-ready system was not presented in Savannah. However, later post-analysis discovered the error and produced revised and favorable results. The final results showed sufficient accuracy for reconnaissance surveys and possibly condition and payment surveys. According to Marconi engineers, the errors have been corrected and the Bathyscan is now a survey-ready system for USACE surveys. Indeed, the capabilities of the system, such as the sonar's wide and dense coverage and the accuracy and consistency of the final results, warrant further investigation of the Bathyscan survey system.

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